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APPLICATION OF DAMPING TO IMPROVE RELIABILITY OF IUS-TYPE SATELLITE EQUIPMENT - RELSAT PROGRAM

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Abstract

A review of the status of the Boeing Aerospace Company (BAC) RELiability of SATellite Equipment in Environmental Vibration (RELSAT) Program is presented. The program objectives, approach, goals and schedule are discussed. The work performed to date includes the selection of the BAC Inertial Upper Stage (IUS) as the baseline system for development in the RELSAT program. A description of work currently being performed is included. This contains typical passive damping design concepts currently under consideration, and component developmental testing and finite element modeling results.

INTRODUCTION

The need for sophisticated military surveillance and scientific observations in space have placed new and increasingly stringent design requirements on satellite systems. These systems must endure the rigors of the launch vibroacoustic environment and then operate precisely in space. In many cases, sophisticated equipment has not survived the high mechanical and acoustically induced vibration levels experienced during launch. These vibroacoustic environments impose severe qualification requirements on satellite equipment. However, current aerospace design practices do not identify critical avionics equipment vibration problems until late in the vehicle design process. The RELiability for SATellite Equipment in Environmental Vibration (RELSAT) program objective is to develop and validate the application of passive damping technology for vibration control to increase satellite equipment reliability. The challenge that is posed to the program is to demonstrate that the early incorporation of viscoelastic damping technology into standard aerospace vehicle design practice can reduce vibration levels and increase equipment reliability without significantly affecting the vehicle weight or program costs and schedules.

The application of viscoelastic material (VEM) has the potential to provide cost effective minimum weight solutions to vibration problems. Recent advances in this field have been numerous and cover a wide variety of disciplines. In particular, RELSAT technology will examine new materials having improved damping properties which can be accurately characterized to enable engineers to select the best, most efficient material for any particular application. Further, modern structural analysis theories will be applied to model structures containing viscoelastic materials (VEM's). In the study of design approaches, the best methods of using these materials will be identified. Although recent advances in materials technology have produced VEM's with greater potential for vibration control, two additional elements are needed to employ them effectively. First, it must be possible to characterize the VEM in a way which is accurate and repeatable. Data must be produced in a readily usable form. Secondly, it must be possible to predict the behavior of real structures which include VEM damping treatments. Both of these elements are RELSAT program goals. The program approach is to design, fabricate, analyze, and test selected damping treatments for structural components and assemblies. This information will be used to develop a damping design for a total system which will be optimized at the systems level for interdisciplinary synergism.

The purpose of this paper is to provide a description and status review of the Boeing Aerospace Company RELSAT Program. This program is funded by AFWAL Flight Dynamics Laboratories under the direction of Dr. Lynn Rogers and Mr. Robert Gordon.

PROGRAM DESCRIPTION

The RELSAT program effort is being conducted in seven major tasks which are scheduled to accomplish the program objectives in a timely and economic fashion.

Task 1 is the complete planning of the program, including details of schedules, tasks, and resources.

Task 2 is the selection of an existing satellite system as a baseline for development in this program. Systems level design requirements and performance goals for launch and satellite operation will be established. A Dynamic Test Article (DTA) will be selected from the baseline system.

Task 3 is a design development activity which will establish a damping design for the DTA. Passive damping concept generation, technology integration, structural analysis and element testing will be performed.

Task 4 is the fabrication of the DTA, and includes the design and construction of all necessary tooling, fixtures, and jigs necessary to fabricate and test it.

Task 5 is the ground test of the Dynamic Test Article to fully characterize its dynamic performance.

Task 6 is an assessment of the impact of the ground test results on the reliability and performance of future space systems. Technology issues requiring further work will be identified.

Task 7 is technology transfer. It consists of timely oral, visual, and written presentations of program progress and results to the United State government and aerospace industry.

The Boeing Aerospace Company (BAC) has the prime responsibility for the conduct of the RELSAT Program. CSA Engineering, Inc., Anatrol Corp., and the Boeing Commercial Airplane Company (BCAC) will assist BAC in accomplishing the program. Figure 1 illustrates the approach that will be used to combine the efforts of BAC, CSA, Anatrol, and BCAC to achieve the program goals.

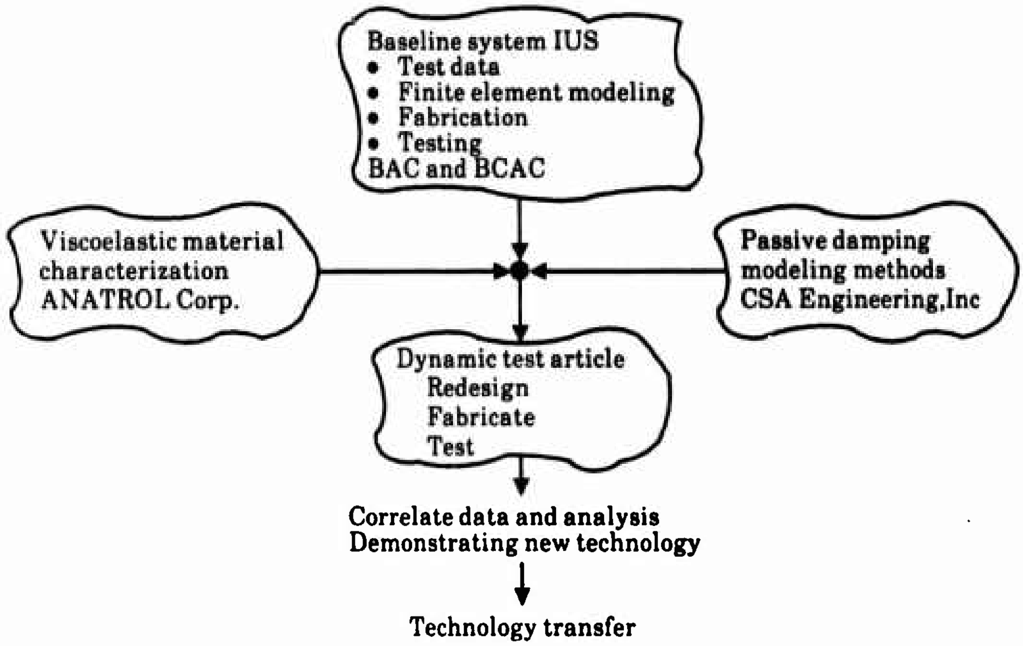


Figure 1: RELSAT Program Approach

Figure 2 illustrates the RELSAT program schedule. This schedule delineates the time allocated for each task and indicates the major milestones critical to the program. The contract was started in March 1983, with a total performance period of five years. The following sections of this paper will describe the current status of the program and some of the technical results obtained to date.

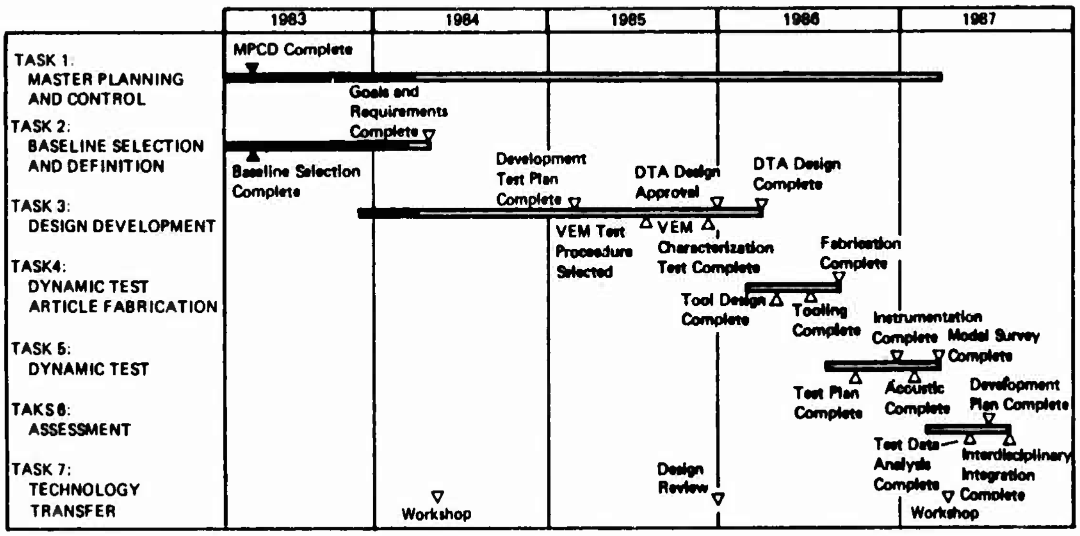


Figure 2: RELSAT Program Schedule

BASELINE SYSTEM SELECTION

The BAC Inertial Upper Stage (IUS) was selected as the baseline system. The following rationale was used for selecting the IUS: 1) the IUS structure is similar to other satellite systems; 2) there exist more than 500 IUS vibration and acoustic measurements which define equipment environments for a variety of structural configurations; 3) the IUS is designed to operate in the Space Shuttle and the Titan launch vehicles; 4) the IUS vibration data are characteristic of other satellite systems; 5) the measured IUS vibration levels are of the magnitude that degrade avionics equipment reliability and performance.

The IUS is shown in figure 3. Like most satellites, it contains avionics mounted on an equipment support section (ESS), propulsion devices and interstage structure. It also has

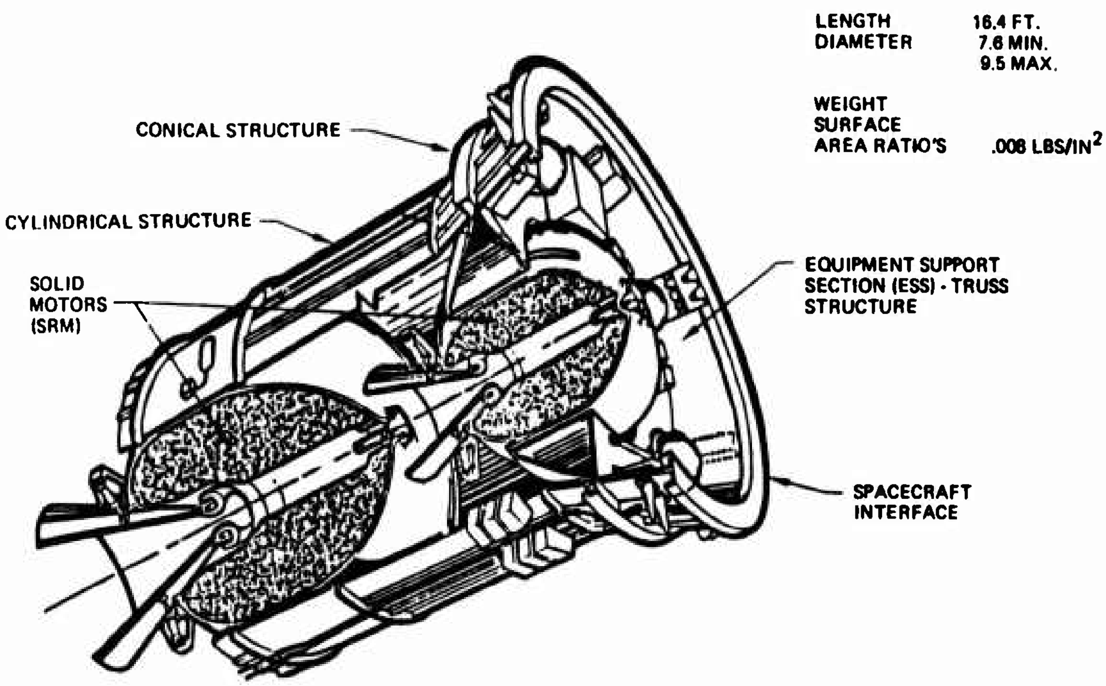


Figure 3: Internal Upper Stage (IUS) Selected for Baseline System

separation devices and structure for interfacing with other vehicles. The interstage and ESS structures are significant structural components for the RELSAT program because they support equipment items and provide vibration environments to the equipment. These structures are lightweight but have large surface areas, which results in high vibration response to noise. The ESS and interstage structure weight-to-surface area ratio is approximately 0.008 pounds per square inch. Other satellites such as the Tracking and Data Relay Satellite (TDRS), the Defense Support Program (DSP) Satellite, and the Defense System Communication Satellite (DSCS) have similar weight-to-area ratios. This type of structure can effectively utilize VEM damping treatments.

Another important reason for choosing the IUS as a baseline was the large amount of available vibroacoustic data. More than 500 vibration and acoustic measurements were made to define the equipment vibration environments. These measurements were made during acoustic tests performed on an IUS Dynamic Test Vehicle (DTV).

The 145 dB noise level applied during the DTV acoustic tests was the design level for payloads carried in the Space Shuttle and the Titan launch vehicle. This acoustic noise environment occurs during launch vehicle liftoff and flight. The IUS vibration response to this noise environment was the highest vibration environment encountered during the IUS mission and defined the equipment design vibration levels. The IUS design vibration levels are in the order of 10 gs rms.

The equipment design vibration levels for other satellite systems are also the result of launch vehicle noise. Since the IUS structure is similar to other satellite structures, the design vibration requirements for equipment are similar. This similarity supports the choice of the IUS as a good baseline system for generic demonstration of vibration control for satellite equipment.

Launch induced vibration levels of the magnitude experienced by the IUS can degrade equipment performance and reliability. Reliability data from MIL-STD-756 indicate that boost vehicle induced environments for satellites are 80 times more severe than orbital environments. This difference is attributed to the vibration and shock environments at launch (reference 1).

The IUS Dynamic Test Vehicle (DTV) was selected as the Dynamic Test Article (DTA) for the RELSAT Program. The IUS DTV has been selected as the DTA for the following reasons: 1) the DTV configuration and structure simulates the operational vehicle static and dynamic characteristics; 2) five vibroacoustic tests and a modal survey were conducted on the DTV to define equipment design vibration requirements; 3) the DTV is available for use in this study.

The DTV was fabricated during the development phase of the IUS program to serve as a static and dynamic test article for development of the production vehicle. A picture of the DTV assembled for an acoustic noise test is shown in figure 4. The configuration and major structural components of the DTV are similar to the IUS flight vehicles. The equipment vibration design and test requirements were obtained from acoustic tests on the DTV.

The five vibroacoustic tests summarized in figure 5 were conducted to define the vibration design requirements for IUS equipment. More than one test was conducted because the magnitude of the noise induced vibration levels created an avionics equipment design problem. During the tests, modifications were made to the IUS structure in an effort to reduce the vibration environment and to understand the interaction between the structure response and the applied noise excitation. Viscoelastic damping material was

applied during test 3. The damping material reduced the vibration response. A modal survey was conducted as part of test 3. The test examined significant vibration modes in the 50 to 300 Hz frequency range. Test 4 was conducted to determine whether IUS vibration response was affected by the acoustic test facility characteristics. Test results showed that the IUS vibration response was independent of the test facilities. Test 5 was conducted as part of a study to design an IUS simulator for use in satellite acoustic tests. The test consisted of measuring the vibration response to 145 dB overall sound pressure level noise excitation. This was done with and without the IUS interstage installed. The test results indicated that the interstage is a significant contributor to the IUS ESS vibration environment.

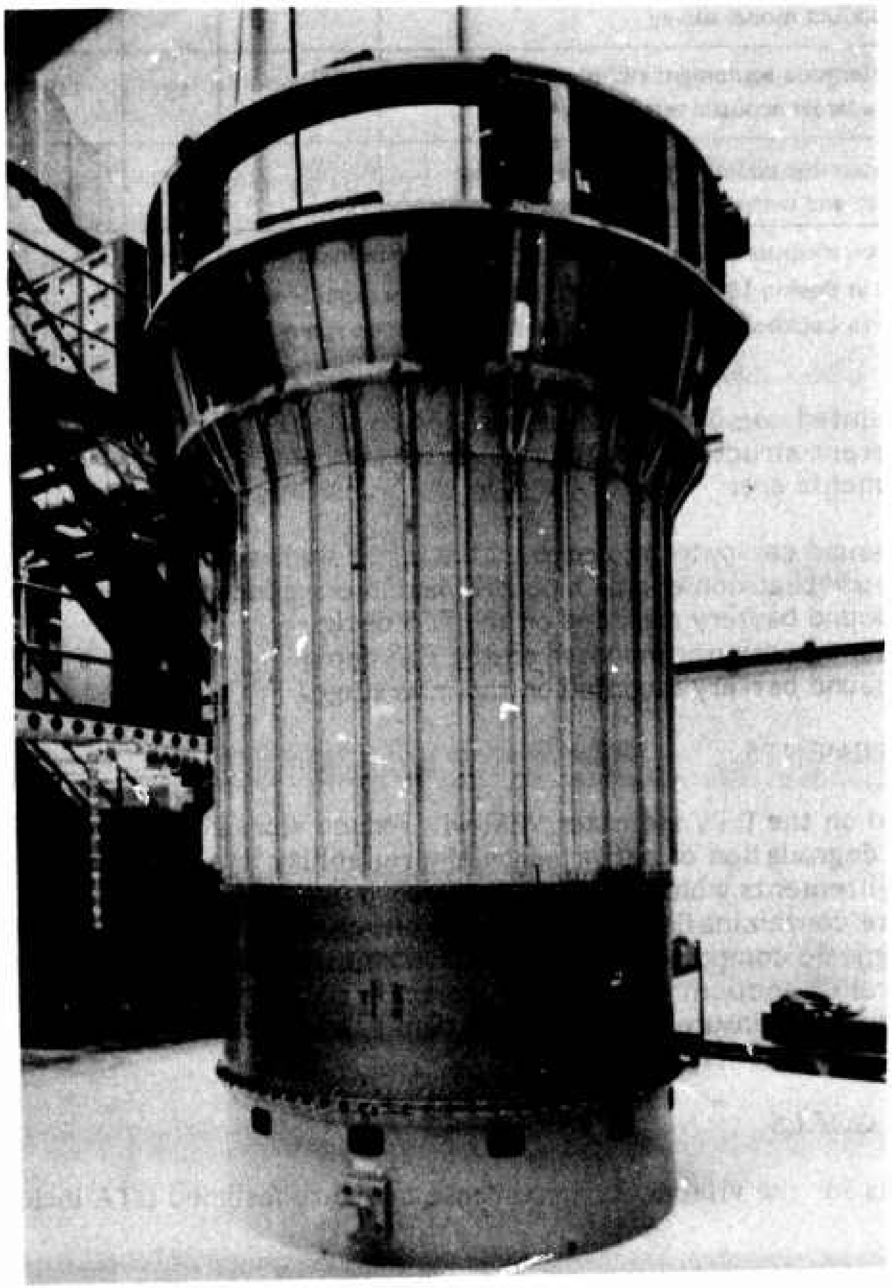


Figure 4: IUS DTV Assembled for Acoustic Noise Testing

TEST NO.	PURPOSE	MEASUREMENTS VIBRATION [1]	NOISE [2]	TEST LEVEL OVERALL SPL dB
1	Determine equipment vibration response	42	5	139 145 [3]
2	Determine equipment vibration response on a modified equipment support section	17	5	145 [3]
3	Determine equipment vibration response 1) One stage configuration 2) Two stage configuration 3) With and without viscoelastic damping Conduct modal survey	53	8	145 [3]
4	Determine equipment vibration response in a larger acoustic test facility	53	13	145 [4]
5	Determine equipment vibration response with and without the IUS interstage	38	5	145 [3]

[1] Vibration measured 20 to 2000 Hz [2] Noise measured 31.5 to 10,000 Hz
[3] Tested in Boeing 16 ft x 24 ft x 20 ft reverberation room
[4] Tested in Lockheed 86 ft x 50 ft x 44 ft reverberation room

Figure 5: IUS DTV Vibroacoustic Tests

A number of simulated components were installed on the DTV. Five have been selected to represent different structural configurations for studying damping design concepts. These five components are:

1. a 50 pound computer mounted on the conic shell structure;
2. a 5 pound reaction engine mounted near the spacecraft attachment ring;
3. a 20 pound battery mounted on the ESS deck;
4. a 3 pound encrypter mounted on the ESS deck;
5. a 45 pound battery mounted on the interstage.

SYSTEM REQUIREMENTS

Testing conducted on the DTV indicates VEM will reduce vibration, but this advantage may be offset by degradation of performance and reliability in another part of the system. System requirements which are likely to impose constraints on the DTA vibration control designs are contamination (outgassing), thermal and electrical conductivity, hardening (electromagnetic compatibility and electromagnetic interference), structural strength, structural deflection, and weight. Vibration control designs considered for the DTA will be reviewed to ensure that maximum damping is obtained with a minimal impact on other system requirements.

PERFORMANCE GOALS

Performance goals for the vibroacoustic response of the redesigned DTA include the following:

- Reduce overall vibration levels (0 to 2000 Hz) at IUS equipment locations to 6 grms or less.
- Limit acceleration power spectral density levels in the 100 to 300 Hz frequency range to 0.1 g^2/Hz.

Figure 6 compares these goals with measured vibration spectra from the DTV. The spectra were measured at IUS avionics support points during a 145 dB acoustic noise test.

These performance goals were chosen because the vibration reduction should be large enough to increase avionics reliability. Also, the 6 grms level corresponds to the minimum vibration design level specified in MIL-STD-1540A. Reducing satellite vibration to this level would make it possible to incorporate MIL-STD-1540A qualified equipment into a new satellite system with no additional qualification testing. This could greatly reduce the cost of future aerospace programs.

The 0.1 g^2/Hz limit over the 100 to 300 Hz frequency range was chosen because of avionics and IUS vibration response characteristics. Avionics chassis and internal circuit boards characteristically have first mode resonant frequencies in the 100 to 300 Hz frequency range (reference 2). Since vibration induced failure is likely to occur in the first mode, it is beneficial to limit vibration input to the avionics box over this frequency range. Figure 6 shows that in the 100 to 300 Hz range the IUS DTV vibration input to avionics is high. Therefore, reducing these high levels will significantly increase avionics reliability. These goals will require spectral peak reductions of approximately 10 dB.

DESIGN DEVELOPMENT

The BAC RELSAT Program is currently involved in the performance of the Task 3 Design Development. This task includes all activities necessary to establish the detailed design

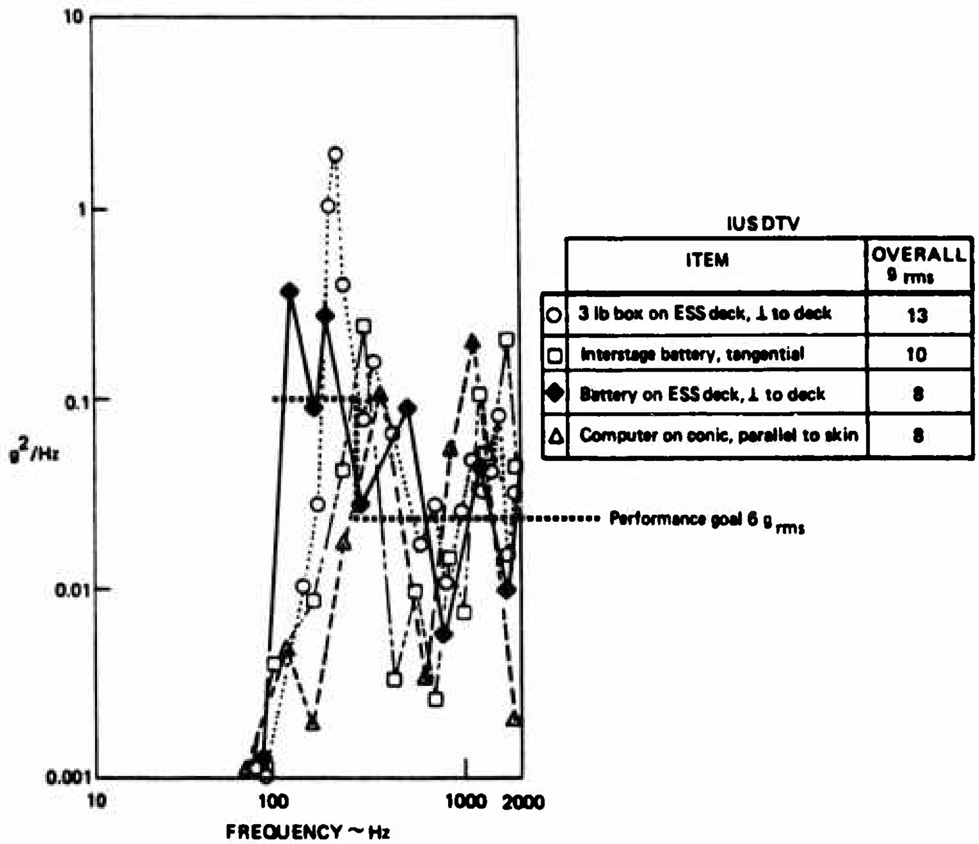


Figure 6: Performance Goals for Redesigned DTA Compared with Baseline Vehicle Vibration Environment

of a damping treatment for application to the DTA. Current efforts are being focused on the development of passive damping design concepts, component developmental testing and finite element analyses, and VEM characterization. The results of these efforts will provide the preliminary data required to initiate the analysis and design activities for the DTA.

DESIGN CONCEPTS

One of the reasons for selecting the IUS as the baseline system was that it contained representative structural components on which a wide variety of VEM damping design concepts could be studied. The design concepts activity is being performed by BAC with support from BCAC, CSA Engineering, and Anatrol. Design concepts are currently being developed which will lead to a full understanding of the benefits and limitations of applying viscoelastic damping to the baseline system. Anatrol is reviewing data on available VEM's and will 'ect the most promising for incorporation into the design concepts. CSA Engineering is conducting analyses to support the damping design concept studies. BAC has fabricated a representative test structure on which the effectiveness of the damping concepts can be assessed. Promising concepts are being fabricated and applied to the test structure which is then subjected to vibration, shock and acoustic testing to determine the effects of the addition of the damping treatment. The detailed knowledge of the IUS baseline system structure and system requirements is aiding in the proper selection of VEM's for development testing and the generation of damping concepts which can be efficiently incorporated into the DTA design.

Some promising design concepts that are currently being considered are shown in figure 7. The concepts shown in figures 7a, b, and c are additive constrained layer treatments that can be applied to the IUS skin panels. Figure 7d shows link and web dampers or integral damping treatments that may be applied to the frame members of the equipment support section shelf. A type of link or axial damper is shown in figure 7e wherein

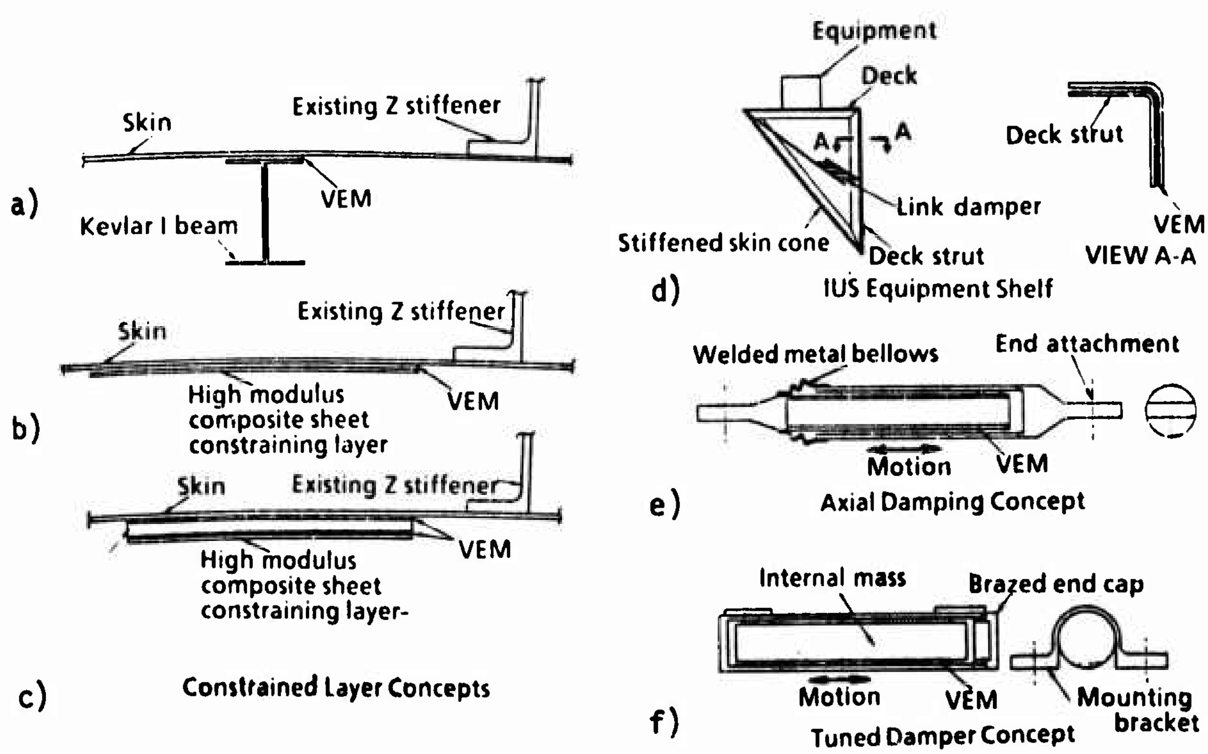


Figure 7: Typical VEM Damping Design Concepts

two close fitting cylindrical sleeves cause shearing motion in the VEM as they move in response to the relative axial motion between the two points of attachment. A tuned damper concept in which a cylindrically shaped free mass on the inside of a sealed unit would cause shearing of the VEM is shown in figure 7f. Other design concepts which are being considered are the use of vibration isolation or composite and injection molded structural components using lossy matrix materials.

The selection and characterization of the VEM that will be used with the damping concepts is currently being performed by Anatrol Corporation. Figure 8 illustrates the procedure that is being followed in determining which VEM will be used with the DTA design. Data from the existing literature is being screened according to two criteria. First, their relevance for satellite application in general will be assessed, and then their applicability to the IUS in particular. From this data list, four materials will be selected for consideration on the RELSAT program. One of these materials will have been sufficiently characterized in the literature so that further testing will not be required. Two other materials will be selected for use in establishing a well defined characterization procedure. Following establishment of a procedure, it will be used to characterize the two materials. Characterization tests will be conducted on the one remaining material to complement the existing data and to verify the recommended characterization procedure. The VEM data will be used to evaluate design concepts using component testing and Finite Element Analysis (FEA) and eventually in the development of the DTA design.

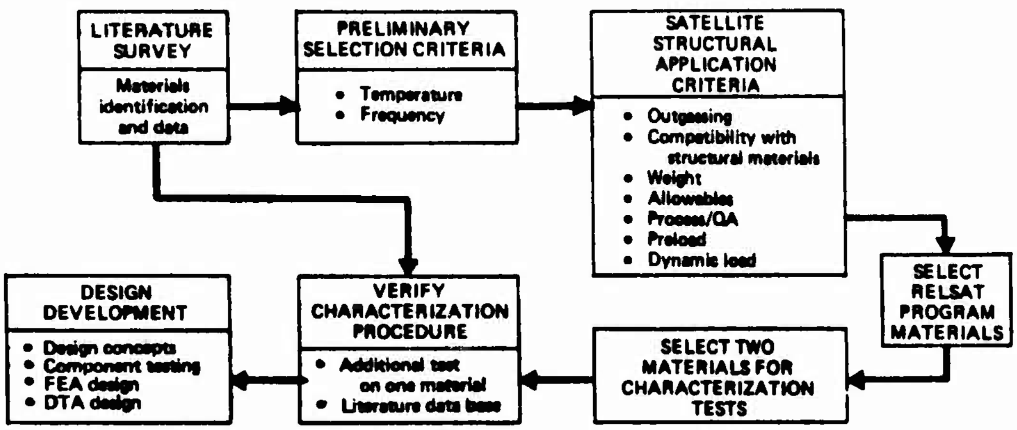


Figure 8: VEM Evaluation Procedure

COMPONENT TESTING

From previous testing performed on the DTV, it was known that the IUS interstage and equipment support section transmitted acoustically induced vibration to the avionics equipment. Therefore, a component test structure which represents a segment of the IUS second stage, second stage motor support cone, and equipment support deck between two spacecraft support longerons was designed and fabricated. A drawing of the component test structure is shown in figure 9. A picture of the test structure with a simulated electronic component mounted on the equipment deck is shown in figure 10. The structure is aluminum skin/stringer construction with all rivets replaced by bolts to facilitate future removal of portions of the structure to add damping treatments.

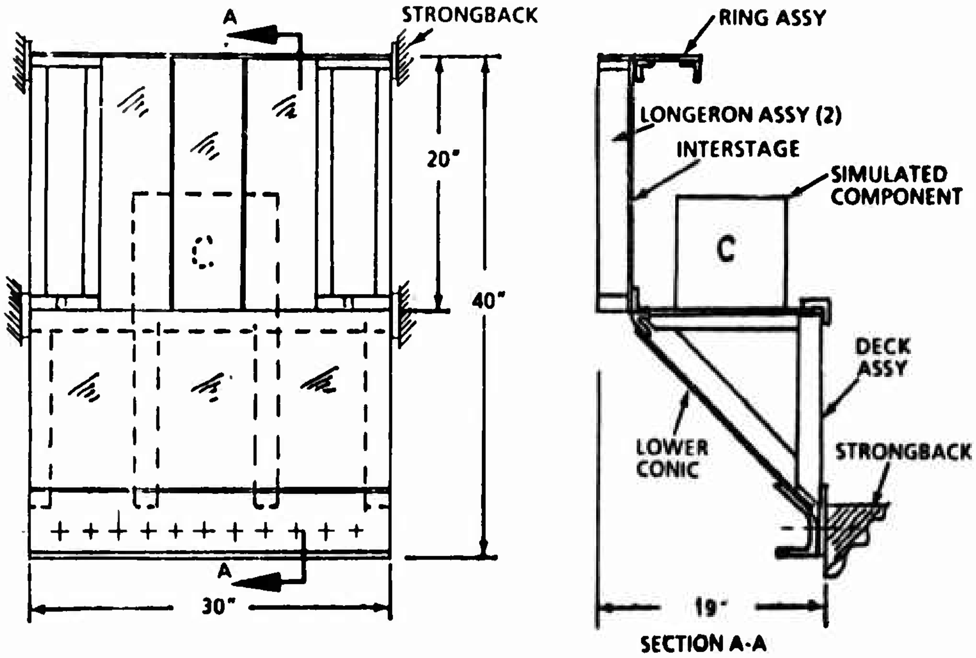


Figure 9: Test Article

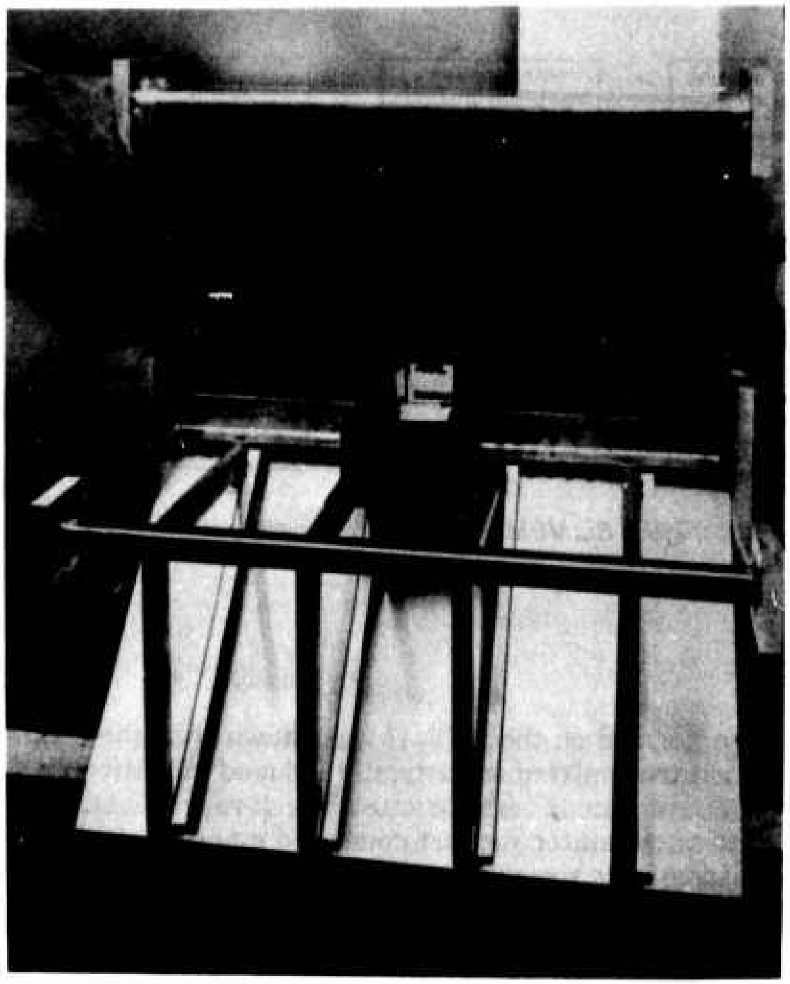


Figure 10: RELSAT Component Test Structure

A modal survey test was performed to determine the mode frequencies and corresponding mode shapes and modal damping values for the test structure. A steel strongback test fixture was fabricated to fix the test structure at the upper and lower rings and along the motor support ring at the bottom end of the lower conic. Figure 11 shows the test article in the vibration test fixture. An electromagnetic vibration exciter was attached to a corner of the simulated electronic component and used to excite the structural modes which contained dominant component motions. The electromagnetic shaker was used to drive the box in the axial, radial and tangential directions. Sine sweeps were run in a frequency range between 50 to 400 Hz. Modal frequencies, damping ratios and shapes were obtained for all of the dominant modes of the test article in that frequency range. This test data is being used as a baseline for the comparison of the effectiveness of the various applied damping treatments, and to compare the results of the analytical finite element modeling.

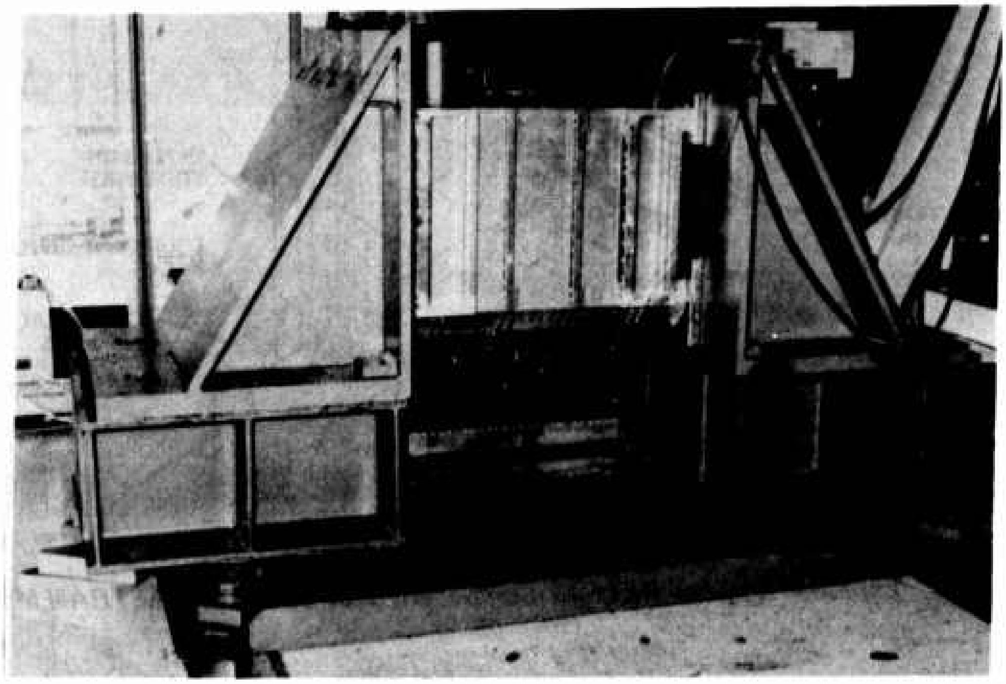


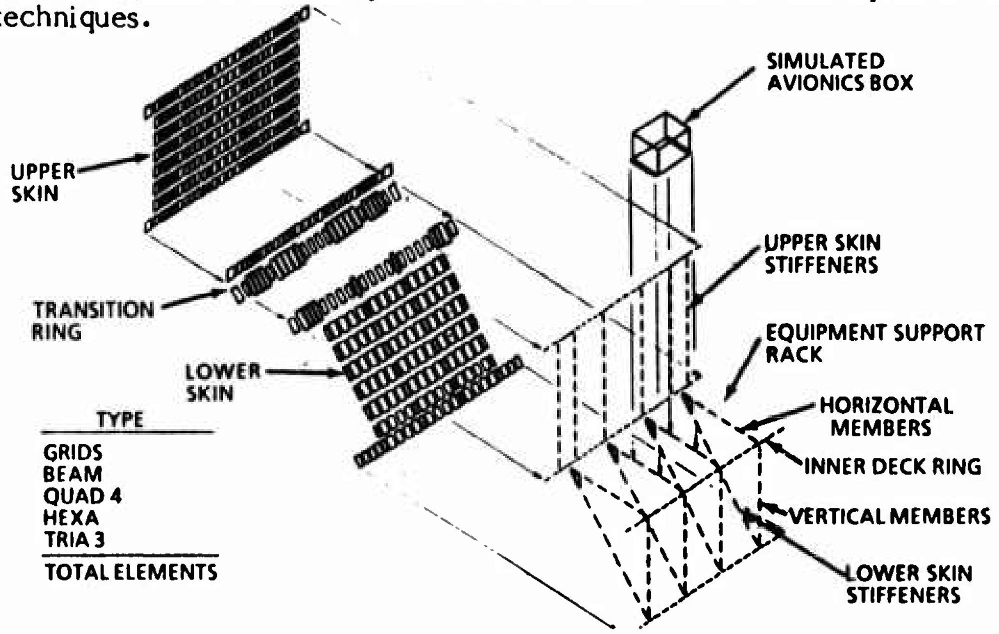
Figure 11: RELSAT Component Test Structure in Vibration Test Fixture

FINITE ELEMENT ANALYSIS (FEA)

Finite Element Analyses are being performed by BAC and CSA Engineering, Inc. FEA will be the primary analytical modeling tool because it is appropriate for the complex structural geometry of the DTA. Also, recent advances in the use of FEA for modeling viscoelastically damped structures make the method particularly applicable for the RELSAT program (reference 3). The primary computer code for all FEA work will be the NASTRAN program.

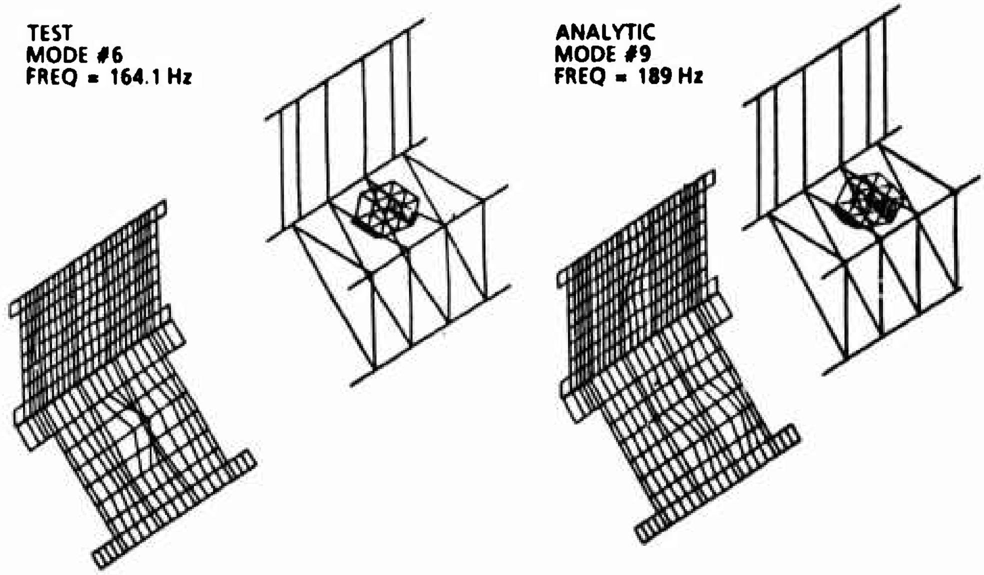
The analysis tasks are broadly divided into two groups: those dealing with modeling the entire DTA structure and those dealing with smaller DTA structural components. It is anticipated that not only will the design concepts be developed by first applying them to structural components and subassemblies, but also efficient analytical modeling methods. New ideas will be tried first with models of easily manageable size so that problems can be isolated and solved one at a time. The design concepts and the FEA modeling techniques developed will then be applied to the detailed design development of the DTA.

A NASTRAN finite element model of the component test structure was developed by BAC to correlate with the results of the modal survey testing. An exploded view of the model is shown in figure 12. This model consisted of 708 nodes and 725 elements. A normal modes analysis was performed in NASTRAN using generalized dynamic reduction. Several major revisions to the model were made before an acceptable correlation with the modal survey tests results were achieved. A visual comparison between predominant electronic component test and analysis modes is shown in figure 13. Although a fairly good correlation with the test results was finally obtained, it was apparent that the finite element modeling would have to be greatly simplified to be practical for modeling the entire DTA. This model is currently being used by CSA Engineering to model the damping treatments to be applied to the component test structure and to develop more efficient modeling techniques.



NUMBER	TYPE
708	GRIDS
259	BEAM
458	QUAD 4
4	HEXA
4	TRIA 3
725	TOTAL ELEMENTS

Figure 12: Exploded View of RELSAT Component Test Structure NASTRAN Model



- Test/analysis comparison of undamped modes
- Modeling must be simplified to analyze DTA designs

Figure 13: RELSAT Component Development Testing Results

SUMMARY

The BAC RELSAT program is a long term effort that is structured to effectively demonstrate recent advancements in passive damping technology. The application and validation of VEM vibration control techniques on a typical aerospace satellite system will demonstrate that damping design can be considered early in the design process for future satellite systems with a minimal effect on the overall system cost and weight. However, before this can happen, the impact of the design damping treatments on the other system level requirements must be addressed. It is anticipated that data developed in the RELSAT program will serve this purpose. During this program, an aggressive effort will be made to transfer the technology to the design community. It is felt that there will be a large potential payoff for future systems in the form of lower avionics equipment costs, savings in the time and cost of qualification testing, and an increase in overall system reliability.

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